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Time Prognosis of Landslide Based on Unstable Creep

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SYNOPSIS The fundamental characters at each of three stages of creep deformation of rock masses are discussed. A model, a friction element and a dashpot element connected in parallel, suitable for middle and short time prognosis is suggested--landslide happens at accelerated creep stage and its mechanism may be described by progressive deterioration (assuming linear decrease with time) of material parameters which denote the friction and the dashpot of rock masses. The verification for the model is carried out by comparing theoretical results with measured results of three typical landslides.

1 INTRODUCTION

Landslide is the most common and important natural disaster specially in mountain areas. It always threats the safety of building and person's life such as railway, highway, navigation and hydroelectric engineering. Further studying on slip mechanism, monitoring the potential slip body, analyzing the measured data in site in time and judging the slip stage and predicting the outburst time, this may provide a chance for us to take prevention measure actively, avoiding or lessening unnecessary loss. There are many factors which affect landslide to form, such as rainfall, flood, earthquake and geological tectonic activity, yet increasing engineering action of human beings (excavation slip, variation of underground water table inducing storing water of reservoir, large scale explosion). But all above are not nature of landslide. The essence of landslides is the change of material properties in slip zone, the other factors are only external causes (Zhang Q., 1986; Feng etal, 1990).

The research on time prognosis of landslide has made great progress. Japanese scholar proposed a empirical differential equation for accelerated creep stage and a time prognosis model was derived out in 1968. After he studied the creep information of rock and soil tested in Lab. and a few monitoring curve in site, Su (1990) suggested that accelerated creep empirically follows hyperbolic law:

$$\frac{dy}{dt} = \frac{at}{b-t} \tag{1}$$

Great progress has made in application of new theories to time prognosis of landslides such as grey theory, time serial analysis and catastrophe theory (Chen,1988; Xue,1988; Miao etal,1988; and so on). That many methods are used to predict the same thing is an access to improve the reliability and precision (Yan,1989).

Displacement -- time curve is not unique characteristic index of landslide time prognosis. Temperature or pore fluid pressure are also other two characteristic parameters: Geothermal field(たけうちとくおす,1985) or pore fluid pressure field (Davis etal,1990) in slip zone may slightly change with sliding.

In this paper firstly author analyses the creep traits of rock masses with comparison to creep curve of rock sample, then proposes a model composed of a dashpot element and a friction element connected in parallel to predict the middle and short term landslide. Finally verification is carried out by three case landslides.

2, PHYSICAL TRAITS OF LANDSLIDES

2.1 Displacement history

Experimental results have shown that the creep of rock sample can be divided into three stages: initial creep, stable creep and accelerated creep (unstable creep) to failure. If a constant stress acts on a rock sample, an instantaneous deformation yields and then deformation increases with time elapsing, curve takes on convex. This part of creep is called initial creep or transition creep (AB section in Fig.1). Following the curve trends to straight line (BE section in Fig.1). Creep enters stable creep or second creep stage. Beyond the stable creep is accelerated creep which creep rate accelerates and may cause failure (EI section in Fig.1). Above three stages exist in the same rock sample if and only if the acting stress is over some critical stress.

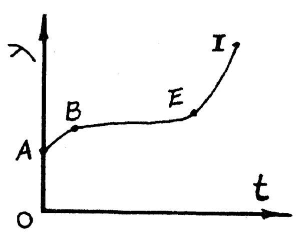

Fig.1 Creep Curve of Rock Sample

AB--Initial creep
BE--Stable Creep
EI--Unstable Creep

Rock mass is a structural system, creep law is more complicated than rock sample and not all creep of landslides experiences above three creep stages. Stopping point depends on structural characteristics and its environments for slippage. It should be pointed out that most of potential landslides stop slipping during stable creep stage. (This stability may be made by engineering treatments such as unloading, drainage and so on), only when external conditions, boundary conditions and internal causes of a landslide make the creep stage into accelerated stage outburst of landslide becomes possible. At this time some traits of landslides behave as follows due to violent change in rock mass specially in shearing zone.

Fig.2 is displacement history y--t curve measured for open mine in Chuguicamate. It obviously shows that the last two creep stages experiences: stable creep stage (a linear section) and then accelerated creep stage(AC, nonlinear section) and failure point at AC stage.

2.2 Acoustic emission phenomenon or microseism

Many measures in site have shown that, frequency of Acoustic Emission (i.e. AE) times to time curve has the same shape as displacement time curve, representing the failure progress of rock mass in different aspects. The non-normal phenomenon of AE is a signal for unstable behaviors during the failing process of rock mass. Microcracks in rock mass increases rapidly and the material of rock mass is damaged continuously. Fig.3 is the record of AE phenomenon when ceiling falling measured by Leighton & Steblay (1975). It also experiences the same curve shape as y--t curve: stable creep stage with small acoustic emission and beyond some point the times increase rapidly until failing. In contrast to above creep curves of rock sample and rock mass following assumption may be drawn: Displacement time curve of rock mass in site is similar to that of rock sample in Lab. This is the basis of proposed model in this paper. In fact, Davis (1990) reveals that pore pressure history in shearing zone has the same curve shape as displacement history curve due to frictional heating. This is a different proof. Davis (1990) also proves theoretically that only when average shear stress exceeds some value landslide becomes possible.

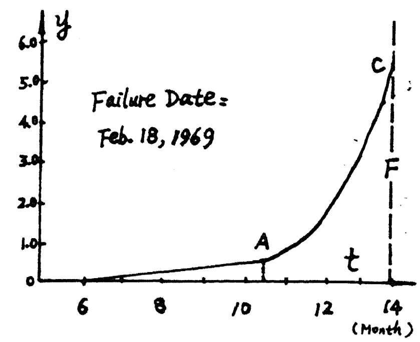

Fig.2 y-t Curve (Open Mine in Chuguicamate)

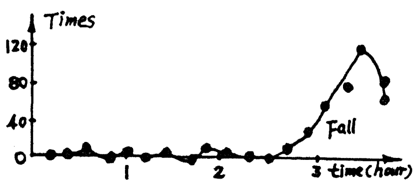

Fig.3 Record of AE When Ceiling Falling (By Leighton & Steblay, 1975)

3 PHYSICAL MODEL OF LANDSLIDES

The task of middle and short time prognosis of landslides is to collect information in accelerated creep stage and to predict outburst time. How to judge the creep enters accelerated stage is an important problem. Zhang (1988) has detailed study on it: after systematically studying the system history for over ten landslides following conclusion may be drawn: The intersection of straight line and curve is the beginning point for accelerated creep stage. Author designs a middle and short time prognosis in Fig.4. Friction element F and dashpot element η are connected in parallel (Omit elastic deformation here). Where W is slide force. Not considering the effect of accelerated velocity, following equation is obtained:

$$W = \eta^*(t)\frac{dy}{dt} + F^*(t) \qquad (2)$$

Then

$$\frac{dy}{dt} = \frac{1-F(t)}{\eta(t)} \qquad (3)$$

where

$$F(t) = \frac{F^*(t)}{W} \qquad \eta(t) = \frac{\eta^*(t)}{W} \qquad (4)$$

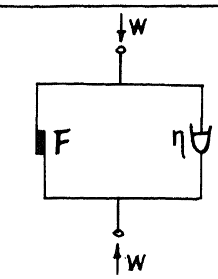

Fig.4 Prognosis Model

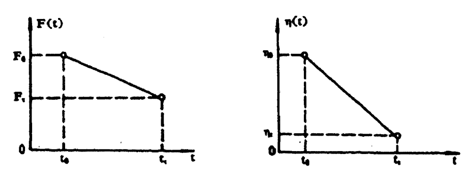

Fig.5 Linear Deterioration of Material Parameters

y is the feature displacement of landslide body; $F^*(t)$ denotes resistance force, $F(t)$ is the friction coefficient approximately in macroscopic meanings, it mainly depends on the friction, fracture and rolling of small grain of rock and soil on slip plane and it decreases until equal to dynamic friction coefficient with slip rate increasing; $\eta(t)$ represents rheological properties of the material on slip plane, mainly depending on the viscosity nature of rock mass. During stable creep stage $F(t)$ and $\eta(t)$ are approximately constants. y is linear function of t known from equation (3). This is in good agreement with observed displacement time curve in site (Zhang,1988).

The physical process from stable creep to accelerated creep can be expressed by the continuous change of material properties on the slip plane. i.e. $F(t)$ and $\eta(t)$ changes continuously, dashpot element transfers the force acted on it to friction element and friction element also deteriorates continuously at the same time. We denotes the parameters at the beginning time t_0 of accelerated creep stage as :

$$F(t_0) = F_0 \qquad \eta(t_0) = \eta_0 \tag{5}$$

The material parameters at outburst time t_τ:

$$F(t_\tau) = F_\tau \qquad \eta(t_\tau) = \eta_\tau \tag{6}$$

Here assume linear transition between two time points (shown in Fig.5):

$$\begin{aligned} F(t) &= F_\tau + \frac{F_0 - F_\tau}{t_\tau - t_0}(t_\tau - t) \\ \eta(t) &= \eta_\tau + \frac{\eta_0 - \eta_\tau}{t_\tau - t_0}(t_\tau - t) \end{aligned} \tag{7}$$

Substitute eq.(7) into eq.(3), we get:

$$\frac{dy}{dt} = \frac{(1 - F_\tau)(t_\tau - t_0) - (F_0 - F_\tau)(t_\tau - t)}{\eta_\tau (t_\tau - t_0) + (\eta_0 - \eta_\tau)(t_\tau - t)} \tag{8}$$

When landslide happens η_τ equal to zero approximately. Eq.(8) can be simplified to:

$$\frac{dy}{dt} = \frac{A - B(t_\tau - t)}{t_\tau - t} \tag{9}$$

Where

$$\begin{aligned} A &= \frac{(1 - F_\tau)(t_\tau - t_0)}{\eta_0} \\ B &= \frac{F_0 - F_\tau}{\eta_0} \end{aligned} \tag{10}$$

Eq.(9) is the equation for middle and short time prognosis based on proposed rheological model (Fig.4).

4 TIME PROGNOSIS OF LANDSLIDE OUTBURST

Using initial condition $y|_{t=t0} = y_0$, solution of eq.(9) is derived out:

$$y = y_0 + A\,Ln\frac{t_\tau - t_0}{t_\tau - t} - B(t - t_0) \tag{11}$$

Now let us simply analyze eq.(11). It is proved that if $F_0 < 1$ there must be $dy/dt > 0$, $d^2y/dt^2 > 0$; and when $t \to t_\tau$ there are $dy/dt \to \infty$, $y \to \infty$, landslide outburst happens. Eq.(11) is suitable for any single rock or soil landslide when creep is in accelerated stage. parameters A, B and t_τ are easily determined from measured data in site. There are two methods for choice to determine t_τ.

4.1 Figure and extension

From eq.(9) we know that $dy/dt \to \infty$ at point $t = t_\tau$. That is to say that $t = t_\tau$ is asymptotic line of dy/dt--t. We may draw curve dy/dt--t and then determine the time t_τ from the curve tendency on dy/dt v.s. t plane.

4.2 Least square method

Denote measured data couple (y_i^0, t_i), corresponding weight w_i (used to exclude the random and observation error) $(i=1,2,\ldots n)$. Then error square sum:

$$\begin{aligned} Q &= \sum_{i=1}^{n} w_i (y_i - y_i^0)^2 \\ &= \sum_{i=1}^{n} w_i \left[y_0 - y_i^0 + A\,Ln\frac{t_\tau - t_0}{t_\tau - t_i} - B(t_i - t_0)\right]^2 \end{aligned} \tag{12}$$

Note: t_0 in eq.(12) is a time point in accelerated creep stage, not requires to be the initial time of accelerated creep stage. This is different from that in eq.(5).

5 VERIFICATION OF MODEL

Three typical case landslides are used to verify proposed model. Measured data are taken from references (Su,1990; Yan,1989). Two happen in China (One is in loess area, the other is at Xilin gorge, the bank of Yangzhi river). The third landslide is the famous Vajont landslide in Italy, the landslide wastes the whole reservoir and over 2900 persons drown. The prognosis results see table 1 and Fig.6-8. It is very interesting to notice such a phenomenon: If we fit the data starting with 22nd Sept., the prognosis time is at noon of 27th Sept. But if the starting point shift to

24th Sept., the prognosis time is 16:48 of 27th Sept., closer to the measured time 17:00 of 27th Sept.(see Fig.6).

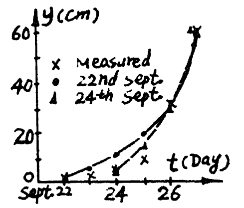

Fig.6 Loess Landslide

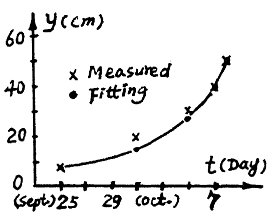

Fig.7 Vajont Landslide

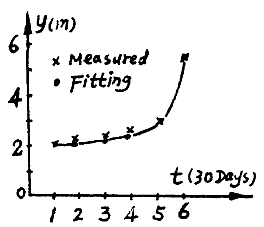

Fig.8 Xintan Landslide

Table 1 Verification of Proposed Model

Case Landslides	Time Measured in Site	Prognosis Time
Loess (North-West of China)	17:00, Sept. 27, 1963	12:00, Sept. 27, 1963
Vajont(Italy)	22:38, Oct. 9, 1963	22:48, Oct. 9, 1963
Xintan(China)	03:45 Jun. 12, 1985	00:00 Jun. 13, 1985

6 CONCLUSION

Through above theoretical analysis and case verification, we can draw out following conclusions:

1), The rheological properties of rock mass have very important effect on outburst time of landslides. Proposed model based on the last two creep stages, stable creep stage and accelerated creep stage, is reasonable and accessible. It can predict outburst time of landslides rather preciously.

2), Assuming that landslide is induced by deterioration of material parameters may explain why landslide occurs and how landslide can be prevented.

3) Distinguish stable creep stage from accelerated creep stage is very important to improve the prediction precision. Even though in accelerated stage we can also replace the older data with newer data to improve the prognosis precision.

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